Final Report for Grant Number N00014-91-J-1808
Summary of Accomplishments and Awards Associated with this Grant
Technical Achievements

- Discovered that the forces on three level can be completely spatially rectified and can have features which can be made arbitrarily narrow even at very low intensities. Extensions of this work have been pursued by P. Gould at UCONN.

- First observation of the forces on three level atoms in Raman Resonant Standing Waves.

- Discovered and described a fully quantum mechanical "dark state" for a standing wave excitation, which has since been studied in detail by P. Zoller's group at Innsbruck.

- Discovered and described the first semi-classical cooling process which can strongly enhance Velocity Selective Coherent Population Trapping. Such a process was later observed at the Ecole Normale in Paris, and investigated by H. Metcalf's group at SUNY Stoneybrook.

- Described the forces on three level atoms in terms of a simply physical picture based on analogies with coupled pendulums. S. Harris of Stanford later used this model to describe electro-magnetically induced transparency.

- Developed and demonstrated the first adiabatic passage beamsplitter for atoms, a technique now being used by S. Chu's group at Stanford.

- Developed and demonstrated a "Non-Magnetic Blazed Grating" beamsplitter for atoms. It showed a momentum splitting of 46 times a single photon recoil, the largest momentum splitting for a continuous beamsplitter.

- Developed and demonstrated a method of attaching micro-lenses to optical fibers.

- Developed and demonstrated a Novel Fiber-Optical Trap for small particles which should permit optical trapping experiments in facilities with very little equipment.

Talks and Publications

- Eleven papers have been published, including two Physical Review letters. Two more have been accepted, and another one has been submitted. Three unsupported papers were published.

- Ten invited talks and 43 other talks at conferences and universities.

Educational Achievements

- Twenty students were partially supported by this grant, including one who graduated with a PhD in 1993. Seven were female, including the following: 4 graduate students, 1 undergraduate, 1 post undergraduate, 1 high school student.

- Arthur Chu won a Hoopes Prize from Harvard College, a Marshall Scholarship, and the Apker Prize from the American Physical Society.

- Mara Prentiss won a Hoopes Prize and the Phi Beta Kappa teaching prize from Harvard.

- Kent Johnson won the Edward L. O'Neil Award for paper presentations at the Optics: Fundamentals and Applications conference at Tufts May 27, 1994, and a Bell Labs Fellowship.

- Two students supported by this work won NSF fellowships.

- There has been considerable popular interest our research, including two articles in Discover Magazine and one in the Economist.

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Final Report for Grant Number N00014-91-J-1808

Atomic Physics Research

We conducted an investigation of the forces on three level Lambda atoms in the presence of Raman Resonant Standing waves. The system is particularly interesting because it possesses a "Dark State" which does not have any excited state population even though it interacts strongly with the optical fields. We studied implications of the force for cooling and trapping as well as atom interferometry and optical lithography. The following discussion of our results will be divided into those categories. All the results are for three level lambda atoms in optical standing wave fields, unless specified.

Cooling and Trapping

When we began the investigation the forces on the atoms in the system were not known. We derived the forces for both stationary and moving atoms, and investigated both the semi-classical and fully quantum mechanical behavior of the system. We showed that the force on a stationary atom has two interesting features: 1. it can be totally "rectified," so that it does not change sign over distances much longer than an optical wavelength 2. it can have features which can be made arbitrarily narrow even in the limit of weak excitation fields. We observed the rectified force experimentally, and also observed that it could also be accompanied by a strong cooling process which cooled atoms below the Doppler limit.

We investigated the cooling theoretically, and found it could be described by a Sisyphus model in which there is a lag between the local state of the atom and the stationary state of the atom, so that the atom is always climbing up hill. This process is different from the Sisyphus models derived before because one of the states is actually a dark state which

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does not interact with the field. In the steady state there is no excited state population, so there is no first order velocity contribution to the excited population, and the cooling coefficient is proportional to the cube of the velocity whereas all other cooling schemes which had been investigated have a term proportional to the atomic velocity. Arthur Chu presented a nice semi-classical model of this process as part of his bachelor's thesis for which he won the Apker Prize.

One of the reasons for investigating this system was the possibility of constructing a light trap for atoms in which the atoms were confined to a "dark state" which has no excited state population. This idea was important because one goal of optical trapping is the observation of collective effects among trapped atoms, and though optical traps are deep and can have substantial damping most groups pursuing collective effects are employing non-optical traps because of the several density dependent loss mechanisms associated with excited states. One of these loss mechanisms is the diffusion associated with spontaneous emission by trapped atoms in the excited state . We first did a semi-classical calculation that showed that there is no diffusion if the differential detuning between the trapping fields is zero. We then derived a fully quantum mechanical dark state which includes both the internal and external degrees of freedom and has zero diffusion. The existence of this state had not been predicted before our investigations, and has since been studied in detail by Peter Zoller's group, which has published several papers using the dark state which we discovered.

We developed a simple physical analogy based on coupled pendulums to describe the behavior of the dark state. This model has since been used by Steve Harris at Stanford to describe optically induced transparency.

We did not build a dark-state based optical trap because detailed simulations suggested that under most conditions of experimental interest, the damping in the system is so strong atoms entering the trap are confined in local potential minima rather than at the center of the trap. Phil Gould at the University of Connecticut at Storr's has since been investigating the force on a three level atom in a ladder configuration, where the local trapping is less marked.

Atom Interferometry

Atom interferometry has made enormous progress in the last few years. There are now five or six groups in the world with working systems. When we started our research, the beamsplitters used in the experiments typically split the atomic beam with a momentum split of the order of two single photon recoils. In many atomic interferometry applications it is desirable to have much larger splitting between the atomic wavepackets. Under this grant, we developed and demonstrated an adiabatic passage beamsplitter based on a suggestion for an adiabatic mirror which was made by Peter Zoller. The technique depends on the existence of the dark state which produced the novel cooling and trapping properties discussed above. The adiabatic passage technique which we developed is now being used by Steven Chu's group at Stanford to obtain momentum splittings of approximately 100 single photon recoils by repeating the adiabatic passage process 50 times.

In addition, we have developed a second beamsplitter which improved upon a design by Pfau et al, which used a combination of a large static magnetic field and light field to produce a "blazed grating" beamsplitter. They produced a splitting of 40 single photon recoils in a single interaction. We generalized their idea and demonstrated a non-magnetic version of the beamsplitter with a 46 photon splitting between the two wavepackets.

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Optical Lithography

Using light to control the deposition of atoms onto a substrate is a new field which has been receiving much interest of late. Thus far, all of the experiments have used the model I developed at Bell Labs in which a standing wave light field is used to focus an atomic beam as it is being deposited onto a substrate. This technique has successfully created one and two dimensional gratings with periods of approximately 200 nm and widths of less than 50 nm. In collaboration with Peter Zoller's group in Boulder we have done some preliminary investigations of applications of three level forces to lithography. We showed that there is an atom field eigenstate of the three level system which is periodic in half the optical wavelength, and is almost perfectly parabolic. It may be possible to use this potential to create much narrower structures than those provided by the sinusoidal potentials that we are using at present.

Other Trapping Projects

We also optically manipulated polystyrene spheres. We showed that light force can be used to align and attach microlenses to single mode optical fibers. Finally, we developed a cheap and simple fiberoptical trap which allowed us to observe spontaneous crystallization among trapped spheres. This crystallization observed among trapped ions several years ago. In both cases the interaction between the external trapping force, and the repulsive force between trapped particles can result in stable configurations of trapped particles. We have seen crystals composed of up to 12 trapped particles.

PUBLISHED REFEREED PAPERS WHICH CITE ONR N0014-91-J-1808:

1. Forces on Three Level Atoms Including Coherent Population Trapping,
    M. Prentiss, N. P. Bigelow, M. S. Shahriar, and P. R. Hemmer, Opt
    Lett, 16, 1629 (1991)

2. Optical Force on Raman Dark State in Two Standing Waves, P. R.
    Hemmer, M. Prentiss, M. S. Shahriar, N. P. Bigelow, Optics
    Communications, 89, 335-342 (1992)

3. Calculation of Enhanced Slowing and Cooling Due to the Addition
    of a Traveling Wave to an Intense Optical Standing Wave, D. Gottesman,
    J. Mervis, M. Prentiss, and N. P. Bigelow, Phys Rev A, 46, 356-363
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4. First Observation of Forces on Three-Level Atoms in Raman Resonant
    Standing-Wave Optical Fields, P. R .Hemmer, M. S. Shahriar, M.
    Prentiss, D. P. Katz, K. K. Berggren, J. Mervis, and N. P. Bigelow, Phys
    Rev Lett, 68, 3148-3151 (1992)

5. Aligning and Attaching a Lens to an Optical Fiber Using Light
    Pressure Force, J. Mervis, A. H. Bloom, G. Bravo, L. Mills, F. Zarinetchi,
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    Mervis, F. Zarinetchi, and M. Prentiss, Opt Lett ,8, 325 (1992).

7. Phase-Dependent Velocity Selective Coherent Population Trapping in a Folded
    Three-Level (Λ) Under Standing Wave Exciation, Optics Communications 103,
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8. Continuous Polarization Gradient Precooling-Assisted Velocity Selective Coherent
    Population Trapping, M.S. Shahriar, P.R. Hemmer, M.G. Prentiss, P. Marte, J.
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9. Polarization Gradient Assisted Subrecoil Cooling: Quantum Calculations in One
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    Prentiss, Phys Rev A, 49, 4826-4836 (1994).

10. Demonstration of a Novel Atomic Beam Splitter, J. Lawall and M. Prentiss, Phys
    Rev Lett, 72, 993-996 (1994).

11. Cooling and Confinement Assisted Velocity Selective Coherent Population
    Trapping, M.S. Shahriar, D.P. Katz, A. Chu, M. Prentiss, P. Marte, P. Zoller, T.
    Cai, N. Bigelow, and P. Hemmer ,Laser Physics, Vol. 4, pg. 848 (1994)

SUBMITTED PAPERS WHICH CITE ONR N0014-91-J-1808

1. Semiclassical Calculation of Diffusion Constant for (Λ) System A.Chu, D.P.Katz, and M Prentiss (accepted by Phys Rev A)

2. Polarization Gradient Assisted Velocity Selective Coherent Population Trapping, A. Chu, M. Prentiss, D.P. Katz, M.S. Shahriar, P. Hemmer, P. Marte, P. Zoller (Submitted to Phys Rev A)

3. Demonstration of Non-Magnetic "Blazed Grating" Atomic Beam Splitter, K.S. Johnson, A. Chu, T.W. Lynn, K.K Berggren, M.S. Shahriar, and M. Prentiss (Accepted by Opitcs Letters).

BOOK CHAPTERS WHICH CITE ONR N0014-91-J-1808

1. Laser Manipulation of Atoms and Ions, M. Prentiss, J. Mervis, K. K. Berggren, M. S. Shahriar, P. R. Hemmer, and N. P. Bigelow. Proceedings of the School of Physics Enrico Fermi, North Holland: Amsterdam, 225-237 (1992)

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